Solar Radiation Dynamics during the Total Solar Eclipse on 11 August 1999 in the Territory of Bulgaria

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Results from videospectrometric investigations of the solar radiation during the total solar eclipse on 11 August 1999 in the territory of Bulgaria are presented. The spectral distribution and integral changes in the solar radiation reaching the Earth's surface as well as images of the Sun's disk were registered from an observation post on the line of totality situated on the Black Sea coast. The solar radiation was measured by means of a high-resolution multi-channel spectrometer and a photometer. Black and white images of the Sun's disk were taken using a television CCD-camera through a neutral filter. The examination of the solar radiation dynamics revealed presence of fluctuations in the recorded spectral distributions before and after the eclipse totality expressed in a weak redistribution of the solar energy in the spectral range (480÷810 *nm*) in the limits of 1÷2%. The joint processing of spectrometric, photometric and videometric data disclosed a high correlation ($R \geq 0.9985$) between the integral and spectral changes of solar radiation with time as well as a concomitant correlation between the solar radiation intensity and the changes in the area and the brightness of the unshaded part of the solar disk in the time interval before and after the totality. The applied statistical method (Students' *t*-criterion) proved statistically significant differences at a probability level of $p<0.001$ between the spectral distribution of the solar radiation recorded at time intervals disposed equidistantly before and after the eclipse totality.

Introduction

The quantitative assessments of the solar radiation flux and the variations of its spectral distribution in the visible and near-infrared ranges of the electromagnetic spectrum are of particular interest for examination of the solar-terrestrial influences. This is due to the fact that the main part of solar radiation energy is concentrated in that range and it determines the thermal equilibrium of the Earth's atmosphere. There are very limited in number independent measurements of the spectral flux of solar radiation and there are almost absent any measurements to determine reliably its variations excluding certain changes related with presence of some Fraunhofer lines in active regions of the solar disk [1, 2].

The spectrometric and photometric methods provide data for the full irradiance originating from the Sun and for its radiance in a wide spectral range of the electromagnetic spectrum. At carrying out measurements on the Earth's surface additional data for the spectral transparency of the atmosphere and the changes in the distribution of energy of the Sun's spectrum are obtained.

The videospectrometric investigations of the solar radiation were one of the 11 projects of the international scientific program for observations during the total solar eclipse on August 11, 1999, from the Bulgarian territory [3]. Their main objectives were to follow and analyze the change in the intensity of solar radiation reaching Earth's surface and its spectral distribution in the visible and near-infrared ranges of the electromagnetic spectrum, in order to explore the integral change in solar radiation and to take snapshot images of the solar disk during all stages of the eclipse.

Experiment and data

The measurements on 11 August 1999 were performed from a point of observation located near the town Shabla on the Black Sea coast on the path of the solar eclipse totality [4]. The partial eclipse started at 12^h46^m LT and ended at 15^h33^m LT. The duration of the total eclipse was 146 *sec*. The measurements were carried out in intervals of one minute between the 1st and 2nd (from 12^h44^m till 14^h05^m) and 3rd and 4th contacts of the eclipse (from 14^h17^m till 15^h30^m).

The videospectrometric experiments planned in the scientific program for the solar eclipse observation were performed by means of a complex of measuring instruments. It included a CCD television camera with high sensitivity (optical resolution 400 *lines/mm*, spatial resolution of 500x582 elements), a photographic camera *PRAKTICA*, a high-resolution multichannel spectrometric system "*Spectrum 256*", a photometer *J16 Tektronix*, a computer system for experiment control and data recording, a diffuse white screen, and auxiliary technical means.

The spectral data were collected using "*Spectrum 256"* designed by scientists of the Solar-Terrestrial Influences Laboratory at the Bulgarian Academy of Sciences [5]. The system was developed for the flight of the second Bulgarian cosmonaut and was in successful operation on the manned space station "Mir" [6]. The spectrometer operates in the visible and near infrared ranges (480÷810 *nm*) in 128 spectral channels at a spectral resolution (halfwidth) of 2.6 *nm*. The time of each spectrum acquisition is 25 *msec* and the scanning speed is 40 spectra per second. The spectrometer was mounted on a three-axis adjustable platform enabling to fix its objective optical axis perpendicular to the plane of a diffuse white screen with calcium dioxide coating. The screen was installed at a distance of 3.5 *m* from the objective in a plane normal to direction to the Sun. Recorded data at each time interval included about 70 spectra of solar radiation reflected by the white screen and 100 spectral records of the dark current for all channels. After processing the data set was expressed in absolute units of spectral reflectance, $\mu W/cm^2\ sr\ nm$.

Records of black and white images of the Sun's disk were made by means of a CCD television camera operating in a standard TV mode and a computer system with a built-in module for 8 *bit* digitizing and input of video data. An input objective with a focal distance of 100 *mm* was used. It was supplied with a removable neutral filter, which makes possible to reduce the light flux by a factor of $8{\cdot}10^4$. To track the solar disk and to correct the camera laying there was used an additional fixed along the same axis optical tube with a focal distance of 350 *mm*. The integral changes of the solar radiation were recorded by photometer J16 with measurement range 1:199.000 cd/m^2.

Results and discussion

We recorded 94 images during the eclipse phases before the totality and 73 images after it using CCD-camera. Based on these data the changes of the unshaded area of the solar disk and its brightness were examined [7]. Fig.1 shows several black and white images of the solar disk selected from the set at different stages of the eclipse.

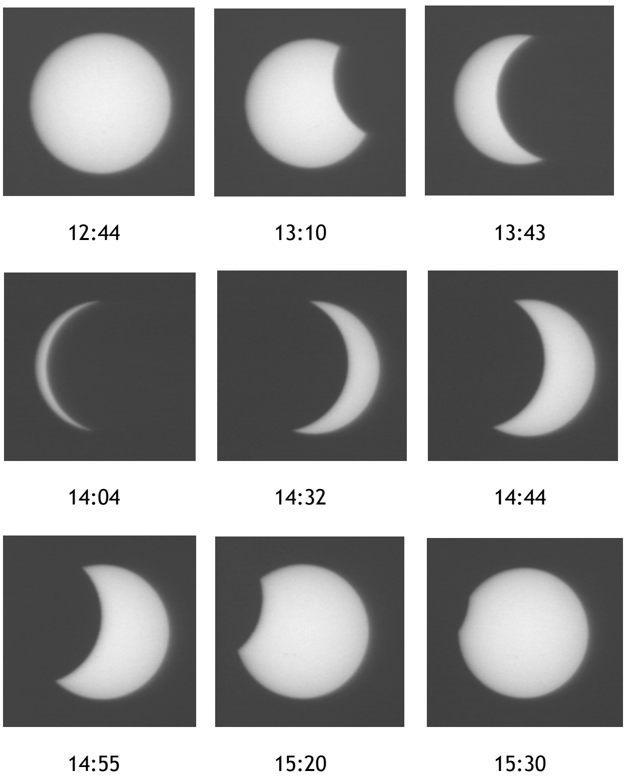

Fig.1. Black and white images of the solar disk selected at different stages of the eclipse.

Making use of the spectrometric measurements of the incident on the Earth's surface solar radiation and after proper data processing we obtained 86 averaged spectra of the solar radiation reaching Earth's surface [8]. A part of them, recorded in interval of time 14^h17^m till 14^h52^m after the eclipse totality, is presented in Fig.2. The spectral characteristic with the highest values of spectral radiance was recorded at 14^h52^m. The spectral data analysis reveals an overall increase of the radiance for all spectra with the time. It is related with the increasing area of the unshaded Sun's disk part and with the irradiating energy delivered after the totality phase until the 4th contact (Fig. 1). The Sun's disk brightness is decreasing from the disk centre to the limb and the analytical expression used to describe the time dependence of Sun's disk darkening was determined from the data in [9].

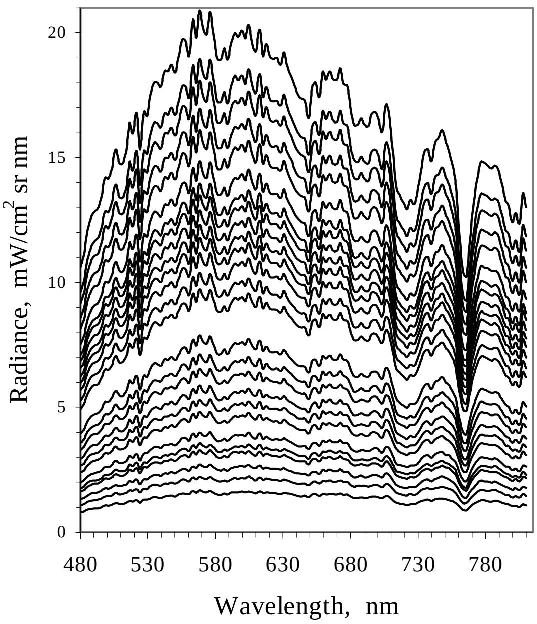

Fig.2. The spectral distributions of the solar radiation in interval of time after the eclipse totality.

Similar course and decreasing radiance with time was observed for the spectral characteristics of the solar radiation between the 1st and 2nd contacts. Fig.3a exemplifies the radiance change in the same time interval in 6 spectral channels at 506 *nm*, 568.4 *nm*, 630.8 *nm*, 672.4 *nm*, 706.2 *nm* and 779 *nm*, which were selected to be equidistantly disposed on the envelope of the spectra recorded.

Fig.3b shows the change in recorded photometric brightness of the white screen $B_e(t)$ (solid line) as well as the function of changed area of the solar disk unshaded part $A_s(t)$ (dash-dot) and the average integral brightness of the solar disk $B_s(t)$ (dot) both determined from the TV images versus time. The product $P_s(t) = A_s(t)\, B_s(t)$ (black circles), which reflects the integral change in the radiance is shown as well. All curves are normalised against the maximum value of the corresponding data in the time intervals between the 1st and 2nd and the 3rd and 4th contacts of the eclipse. The changes in the intensity of incident solar radiation before and after the solar eclipse totality (see Fig. 2 and Fig.3a), were strongly correlated ($R \geq 0.9985$) with the integral photometric brightness recorded synchronously, and with the time dependence of the area and the brightness of the unshaded Sun's disk part which were determined from the video images.

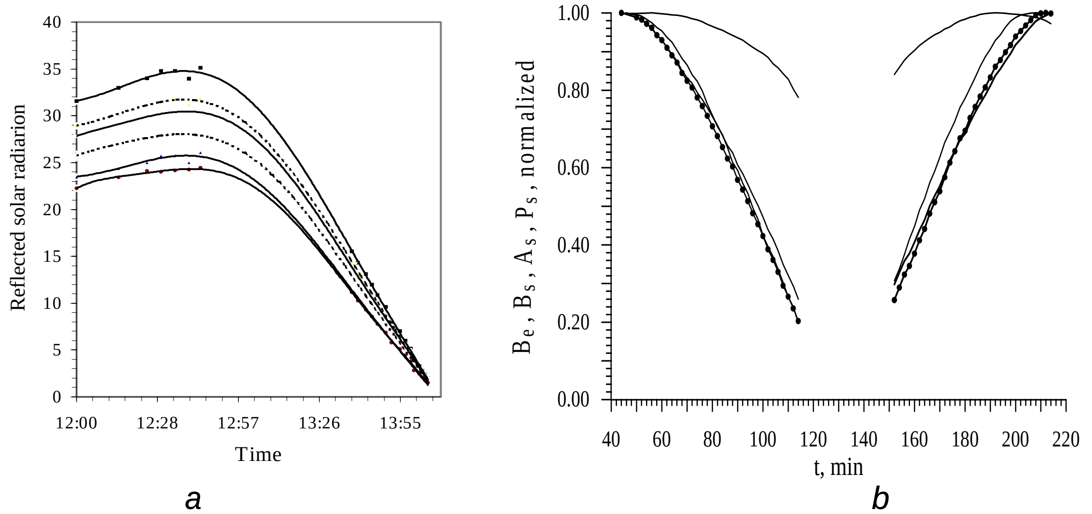

Fig3. a) The variation of the solar radiation in 6 spectral channels before the totality; b) temporal changes of As, Be, Bs and Ps before and after the totality.

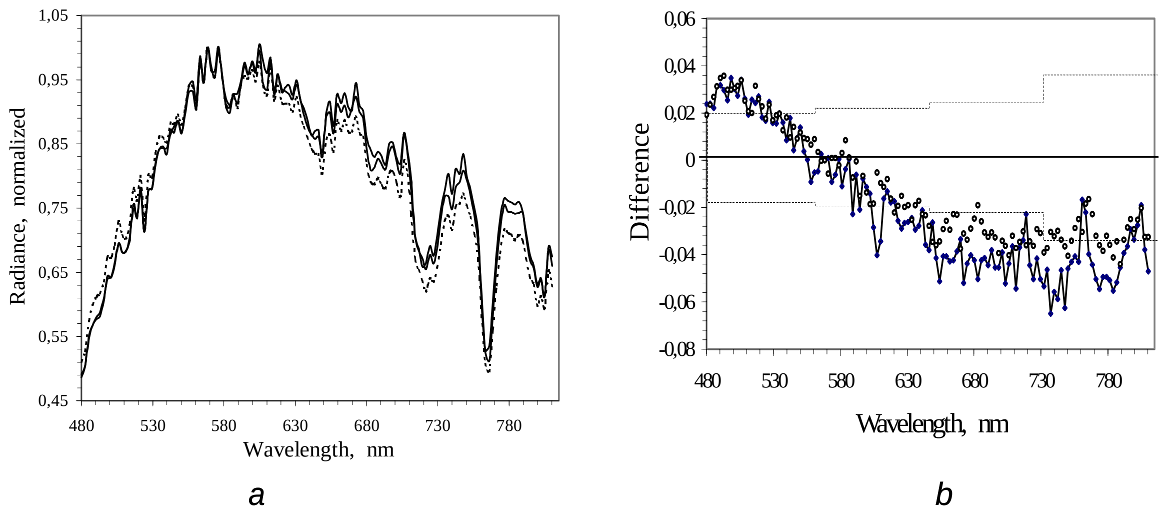

Fig.4. a) Normalized solar spectral characteristics before totality; b) differences between normalized solar spectral characteristics.

The examination of the evolution of the spectral distribution of the solar radiation in time has shown that there was a weakly expressed redistribution of energy within the spectral range studied at the transition from a maximal solar disk radiant area to its minimal area dominated by the Sun's disk limb. This effect is illustrated with Fig.4a wherein the dashed line represents the normalized spectral characteristics taken at 12^h44^m. Solid lines are drawn to show the normalized spectral characteristics taken at 14^h04^m and 14^h05^m before the totality. The effect was expressed as a decrease in the energy of radiation in the 480÷568 *nm* range and its increase in the 568÷810 *nm* range with both changes lying within the limits of 1-2%. There are clearly expressed in the spectra the absorption bands of water vapour and oxygen in the wavelength intervals 672.4÷698.4 *nm*, 747.8÷776.4 *nm* and 706.2÷737.4 *nm*, 786.8÷807.6 *nm*, respectively. Fluctuations were established for the radiance value at the all absorption bands minima as well as of their areas right before and after the totality. Fig.4b shows the differences between the spectral distributions measured at 13^h43^m and 14^h04^m (circles) and at 13^h43^m and 14^h05^m (dotted line) as well as the statistically determined threshold sensitivity of the spectrometer (dashed line).

The spectrometric data of the spectral solar distributions at time intervals equidistantly disposed before and after the eclipse totality were processed and compared by means of statistical methods.

In Table 1 the results of this analysis are given for spectral data recorded in 13^h43^m and 14^h41^m.

TABLE 1

Descriptive statistics of sets of values of the spectrums at fixed wavelengths λ of the envelope, water absorption band and oxygen absorption band

λ [nm]	Mean $\overline{x}_1$	Stand. dev. s_1	Var. coef. V_1 %	Mean $\overline{x}_2$	Stand. dev. s_2	Var. coef. V_2 %
	$13^h 43^m$			$14^h 41^m$		
	Envelope					
506.0	9.556	0.0636	0.67	9.821	0.0418	0.43
568.4	13.102	0.0441	0.34	13.482	0.0542	0.42
630.8	12.076	0.0739	0.61	12.455	0.0524	0.42
672.4	11.711	0.0910	0.78	12.081	0.0524	0.43
706.2	10.806	0.0684	0.63	11.182	0.0717	0.64
779.0	9.329	0.0550	0.59	9.653	0.0550	0.57
	Water absorption band					
706.2	10.806	0.0684	0.63	11.182	0.0717	0.64
721.8	8.129	0.0800	1.05	8.444	0.0618	0.73
737.4	9.687	0.0501	0.52	10.037	0.0717	0.71
	Oxygen absorption band					
747.8	10.122	0.0522	0.52	10.465	0.0782	0.74
766.0	6.517	0.0788	1.21	6.673	0.0627	0.94
776.4	9.390	0.0707	0.82	9.674	0.0680	0.70

The means $\overline{x}_1$ and $\overline{x}_2$, the standard deviations s_1 and s_2, and the variation coefficients V_1 and V_2 of the spectral distributions of the Sun's radiation are given at fixed wavelengths. $\overline{x}_1$ and $\overline{x}_2$ are the means of the measured set of 70 distributions at the fixed wavelengths and for the respective moments of the eclipse - 13^h43^m and 14^h41^m.

The statistical significance of the differences $\overline{x}_1 - \overline{x}_2$ was examined at the wavelengths showed in Table 1. They were chosen as follows: six of them to be relatively uniformly disposed over the envelope of the spectrum distributions; three of them to be within the beginning, the minimum and the end of the interval of water vapour absorption band and three of them to be within the beginning, the minimum and the end of the interval of oxygen absorption band.

The application of the Student's *t*-criterion revealed that all differences $\overline{x}_1 - \overline{x}_2$ are statistically significantly different from zero at p<0.001 and moreover all $\overline{x}_2 > \overline{x}_1$. This may be caused by changes in the atmosphere optical characteristics due to:

a) during the summer clock time the atmosphere temperature (when the atmosphere is not cloudy) rises up to approximately 15^h, so under the condition of equal unshaded areas of the Sun disk before and after the eclipse totality, when the measurements were performed, the temperature was higher during the second stage of measurements;

b) the approximately one hour duration between the two sets of measurements (13^h43^m to 14^h41^m) under eclipse conditions which was may be enough the atmosphere to become clearer from aerosols and other contamination during the second stage of measurements.

The remarkably small variation coefficients in % (Table 1) indicate that the solar radiation characteristics as well as the instrumentation parameters remained almost constant in the frame of each of the stages of measurements (approximately 20 *sec* per stage).

Conclusions

The strong correlation found between the changes of geometrical and radiometric characteristics of the total solar eclipse indicates that the data obtained are not influenced by events of technical and meteorological character.

Regardless of the favourable atmospheric conditions during the measurements changes were registered in the solar radiance within the limits of 1-2 % immediately before and after the eclipse totality.

Furthermore, statistically significant differences were established between the solar radiance values in equidistantly disposed time moments with respect to the totality due to changes in the objective measurement conditions such as atmosphere temperature, aerosol content and zenith angle of the Sun, etc.

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